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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

THE MEASUREMENT OF HIGH HYDROSTATIC PRESSURE.

II. A SECONDARY MERCURY RESISTANCE GAUGE.

By P. W. Bridgman.

Presented by W. C. Sabine, December 9, 1908. Received December 16, 1908.

In the introduction to the first part of this paper it was stated that the end sought in designing the primary gauge was the calibration by means of it of some secondary gauge which should be easily reproducible. The secondary gauge that it was proposed to adopt is one involving the variation of mercury resistance with pressure. This is of an entirely different character from the type of secondary gauge in common use, which is usually some form of metallic deformation gauge like that of Bourdon. Undoubtedly the Bourdon is one of the most convenient forms of secondary gauge that it would be possible to devise, being almost immediate in its action, and capable of standing considerable rough handling. If it were applicable over the wide pressure range contemplated for the mercury gauge, its greater convenience would certainly overbalance the fact that every such Bourdon gauge must be initially calibrated against some direct standard.

It seems to be a fact, however, that any elastic deformation gauge becomes unsuitable at high pressures, even when once calibrated, because of the entrance of hysteresis effects. It is true that the existence of elastic hysteresis effects has frequently been doubted, and it has even been stated that proof of their existence would give us knowledge of a new elastic property. It nevertheless seems to be a fact that hysteresis may be inappreciable at low values of the stress, but become increasingly important at higher pressures. This is not the place, however, to enter into a discussion of this point, which will afford the subject for another paper. But in this paper there will be given a somewhat detailed examination of the behavior under pressure of one Bourdon gauge, which will at least show that this type of gauge is irregular at high pressures, whatever the true explanation of this irregularity may be. This paper will be chiefly concerned with a careful examination of the suitability of the proposed mercury standard, and a determination of the constants necessary to its use up to 6800 kgm. per sq. cm. At the end will be found a calculation from the constants of the mercury gauge of the variation of the specific resistance of mercury under pressure. This calculation involves a knowledge of several compressibilities, which had to be independently determined. In order, however, not to group together in one paper unrelated matter, the determination of compressibilities under high pressures is made the subject of another paper, and only the numerical results there found are used here.

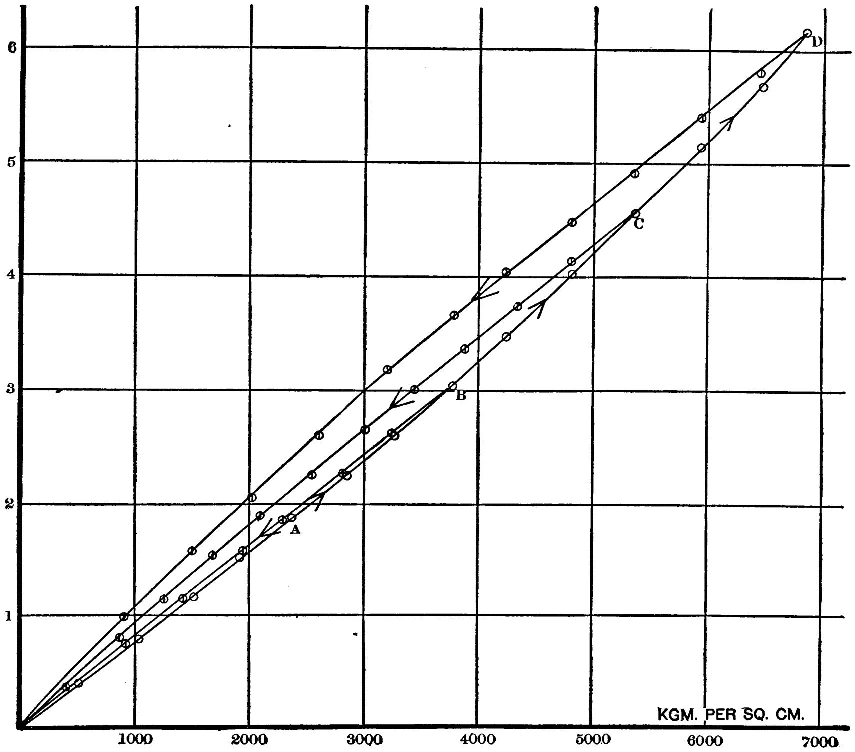

FIGURE 1. Deflection of free end of Bourdon gauge plotted against pressure. Four complete cycles are represented, the points A, B, C, and D being the successive turning points. The figure shows the increasing importance of hysteresis at higher pressures.

The Bourdon gauge used consisted of hard drawn Shelby steel tubing $\frac{5}{16}$ in. (0.79 cm.) outside diameter and $\frac{1}{16}$ in. (0.159 cm.) inside diameter, wound into a helix of five turns of 5 in. (12.7 cm.) diameter. The tube was not flattened into an elliptic cross section, as in the ordinary Bourdon gauge, since to do this would have too greatly decreased the strength. Even when the cross section is left round, however, the tube unwinds upon the application of pressure, like the ordinary Bourdon. The amount of unwinding was read directly by observing the position of the free end with a microscope, a method of reading which proved more satisfactory than any multiplying mechanism. Thus gauge had been in use for upward of six months before the readings shown in Figure 1 were made. The gauge had been so thoroughly seasoned by the many applications of pressure in this interval that the deflections on many subsequent occasions were found to agree within the errors of reading. Initially, the gauge showed some slight set under the maximum pressure, but after the first few applications of pressure no further set appeared. Elastic after effects, which might be expected to be troublesome over this wide pressure range, could be noticed at every stage of the pressure variations, but were too small to appear on the diagram.

In Figure 1 the deflection of the free end (mm.) is plotted against pressure in kgm., which was measured with a mercury resistance that had been calibrated against an absolute standard, as will be described later. The figure shows the effect of applying four cycles of pressure, from zero by steps to the maximum and by steps back to zero, each subsequent maximum being higher than the preceding. Pressure was first applied in steps from zero to A, and then reduced to zero. The return path coincides so closely with the initial path that the difference cannot be shown on the diagram. Pressure was now increased from zero to B and decreased to zero. The first part of the path zero–B coincides exactly with the path from zero to A. The return path B–zero is sensibly linear, but does not coincide with the path zero–B. We have here, then, the beginning of departure from linearity, and also the beginning of hysteresis. Two more loops, zero–C–zero, and zero–D–zero, reaching to higher pressures, were now described. The essential characteristics are the same, but departure from linearity and hysteresis both increase rapidly with the rise of the range. The return paths for these longer loops do not continue linear, as for zero–B–zero, but they both start as straight lines and run for about the same distance before beginning to curve down to meet the origin. The increasing importance of hysteresis is shown by the fact that the greatest error introduced by hysteresis in the loop zero–B is

4 per cent, while in the loop zero–D it is 40 per cent, an increase of tenfold for a doubling of the pressure range. The return path D–zero was not described at the same time as the part zero–D, because an explosion occurred when the maximum D was reached. It is, however, the return path described on another occasion when the initial path zero–D was identical with the above.

Other types of gauge have shown the same characteristics at high pressures. Whatever the true explanation may be, it has been found in every case that an elastic deformation gauge does show behavior like the above. This type of gauge appears, then, to be unsuitable for the accurate measurement of high pressures, and must be replaced by some form not showing hysteresis; for even if this gauge were readily reproducible, the fact that it shows hysteresis would make its indications such a complicated function of pressure, both present and past, that the meaning of the indications could not be conveniently deciphered.

Any scalar physical property when changed by a strain the same in every direction, such as is produced by hydrostatic pressure in a perfectly homogeneous solid, or a liquid, may be expected to show no hysteresis relative to the stress. Such a property, which has the advantage of being easily measured, is electrical resistance. This has been proposed at least twice as a pressure indicator.

Lisell[1] measured the resistance of a number of metals, drawn out into wires, when subjected to hydrostatic pressures up to 3000 kgm. Pressure was measured on an absolute gauge in which the pressure on the freely moving piston was balanced by weights on a lever. Lisell found no evidence of hysteresis, and proposed the measurement of electrical resistance as a satisfactory means of measuring pressure. The variation of resistance of metallic wires, however, was found by Lisell to have the fatal disadvantage for the present purpose of being so greatly influenced by slight impurities in the metal that specimens of the same metal from different sources gave very different results. This gauge, then, would not be reproducible, but each new specimen of wire would have to be calibrated individually against some absolute standard. In addition, the pressure coefficient is inconveniently small, so that great care must be taken to avoid other effects in measuring the slight change of resistance brought about by pressure. Lisell claims as an advantage of this method that the heat of compression of the metallic wires is smaller than for most substances.

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[1] Lisell, Om Tryckets Inflytande på det Elektriska Ledningsmotståndet hos Metaller, samt en ny Metod att Mäta Höga Tryck. Upsala, 1903. (C. J. Lundström.)

De Forest Palmer,[2] working with the high pressure apparatus of Barus, made measurements of the electrical resistance of mercury up to 2000 kgm., and suggested it as a suitable secondary standard. He gives data from which the pressure can be calculated if the change of resistance is known. It appears from his work that the pressure coefficient is large enough to make accurate measurements of the change of resistance easy. The additional advantage of presumable reproducibility made it seem worth while to examine with some care its suitability as a secondary standard. The conclusion reached is that with ordinary care the mercury resistance gauge is good to about $\frac{1}{10}$ per cent.

In order to attain this probable degree of accuracy, however, it was necessary to examine several minor points with somewhat greater detail than de Forest Palmer found necessary for the purpose of his work. The probable error in de Forest Palmer's work was $\frac{1}{10}$ per cent on the total resistance, which means an error of 1.5 per cent on the pressure at 2000 kgm. The percentage error at lower pressures is of course proportionally greater. Within these limits of error he found the pressure coefficient to be constant. Furthermore, the mercury was placed in a capillary of some glass not specified, so that the data given will not apply to other mercury gauges with a greater degree of accuracy than the possible error introduced by variations in the compressibility of the glass. It is known that different grades of glass may differ in compressibility by as much as 100 per cent.

In fact, this matter of the glass containing vessel proved to be the chief source of possible error. Pure mercury may with confidence be assumed to be perfectly reproducible, and since internal strains cannot be set up in it, to be also perfectly free from hysteresis. The glass, however, is a solid in which it is particularly difficult to get rid of internal strains. It cannot be assumed, therefore, that a pure hydrostatic pressure will not produce hysteresis, or even set analogous to the volume set shown in thermometers after exposure to changes of temperature. It is an advantage, however, that the total effect of the glass envelope is unusually small, both because of the comparative largeness of the pressure effect on the resistance of the mercury, and because the correction factor is only $\frac{1}{3}$ instead of the whole of the compressibility. This latter fact is due to the simultaneous shortening of the capillary which contains the mercury, and the decrease of the bore, the one resulting in an increase of resistance and the other in a decrease. The total correction on the observed change of resistance introduced by the glass envelope is only 2.5 per cent as against 60 per cent in determinations of the compressibility of mercury. Hysteresis and other irregular action will appear, therefore, simply as perturbations of this 2.5 per cent correction. There are a number of smaller sources of error, which, even though very obvious, will be mentioned as occasion presents, because in the justification of a new standard it seems well to record all the sources of error that were considered or guarded against.

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[2] de Forest Palmer, Amer. Jour. Sci., **4**, 1–9 (1897), and **6**, 451 (1898).

The electrical measurements were carried out on a bridge of the Carey Foster type provided with an eight point mercury switch. The variable mercury resistance took the place of one extension coil, and the other was a manganin coil of approximately ten ohms. Measurements were made by setting the slider for no deflection, this being preferable to measuring the current by ballistic or steady throw of the galvanometer. A D'Arsonval galvanometer of low resistance was used, of sensitiveness great enough to indicate changes in the position of the slider of less than $\frac{1}{10}$ millimeter. Extension coils and balancing coils were of seasoned manganin, all approximately ten ohms. In comparing together two mercury resistances the same balancing and extension coils were used, the bridge being provided through leads of $\frac{1}{4}$ in. copper wire of negligible resistance with two slide wires one meter long. The slide wires were interchanged by mercury switches frequently cleaned. The resistance of the extension and balancing coils, as well of the bridge wire, was measured against standard manganin coils known to be correct to 0.01 per cent, which were kindly loaned for the purpose by Professor B. O. Peirce. The bridge wire was calibrated for uniformity by stepping off on it a resistance equivalent to approximately 10 cm. at 3 cm. intervals. The maximum correction of one wire was 0.4 mm., of the other 0.7 mm. The average arithmetic correction of the first was 0.17 mm., of the latter 0.4 mm. Approximately 33 cm. of either wire has a resistance of one ohm. All the connections in the circuit were either soldered without acid for a flux or were through mercury cups, except two connections at the insulating plug leading to the mercury resistance, which were made with nuts. As it was found that induction effects were unnoticeable, the bridge was operated with the galvanometer circuit permanently closed, thus eliminating the principal sources of thermal currents. Two readings of every resistance with the extension coils interchanged were really unnecessary, therefore; but they were always made so as to secure the increased accuracy of two independent settings. Current was supplied by a single Samson cell of about one volt, and was decreased by inserting 100 ohms in the battery circuit. The current through the mercury resistance was therefore about $\frac{1}{220}$ ampere. It was necessary that the current be about as small as this to avoid heating effects in the very fine mercury thread. With this low current, however, the key might be closed indefinitely, with no apparent change in the resistance of the mercury.

In carrying out the measurements, the first and most considerable difficulty that presented itself was the designing of a suitable insulating plug for leading the electrical connections into the pressure chamber. Amagat, and most investigators following him, have used as insulating plug a cone of steel (B, Figure 2) separated from the surrounding walls of the pressure chamber by a thin layer (A) of hard rubber or ivory. Any such arrangement as this proved unsuitable for the pressures dealt with here, the hard rubber flowing completely out of the conical crevice, and exuding in the form of a more or less continuous cylindrical tube. Various modifications of this, using the tougher red fibre instead of hard rubber, were tried with little success. Silk also was used as an insulating material and with better success. The silk was cut out in the form of a number of discs and placed around the shank of the cone, which was then forced into its seat. It was found advisable to make the cone and its shank from one piece of steel, otherwise they were pulled apart by the friction of the silk. This form of plug has a high enough insulating resistance and is tight, but has the disadvantage of not being permanent. After ten or twenty applications of pressure the silk loses all semblance of structure, and leaks more and more rapidly with every successive application of pressure.

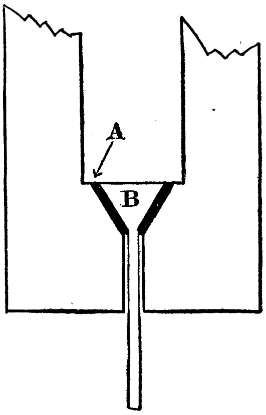

FIGURE 2. Amagat's insulating plug. A, insulating shell of hard rubber or ivory; B, cone of steel. At high pressures the insulating material, A, flows out of the crack.

The cone was now given up and mica tried for insulation, tightness being secured by a layer of marine glue (G, Figure 3). The mica showed no tendency to flow or crumble at the unsupported edge at A. This device was much better than the silk, but it too was not permanent, the marine glue being eventually forced past the mica washers which were a drive fit in the hole. In the form finally adopted (Figure 4) the mica insulation is kept, but tightness was secured by a layer of soft rubber, R, between the mica washers, M. The small steel washer S was necessary to prevent the rubber forcing its way past the mica next the stem, where it is unsupported by the steel at the rear surface. G is an insulating tube of glass. It is well to secure the steel piece B against working loose by the nut and hard rubber washer at A. This plug is the most permanent so far found; one has been subjected to 6500 kgm. upward of seventy times with no sign of leak. The insulation resistance of these plugs is high enough for the work in hand. Initially it is over 10, meg-ohms. With successive applications of pressure the resistance drops considerably, finally

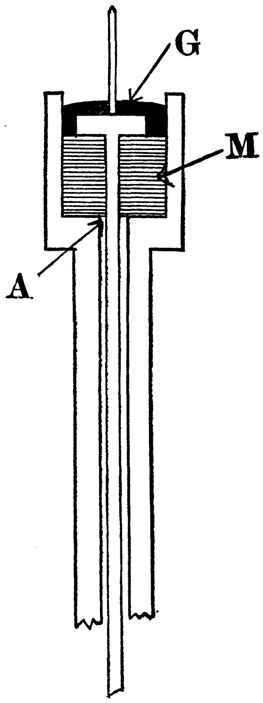

Figure 3. Preliminary form of insulating plug for higher pressures. M, mica washers; G, marine glue to prevent leak. Eventually the glue is forced by the pressure past the mica washers.

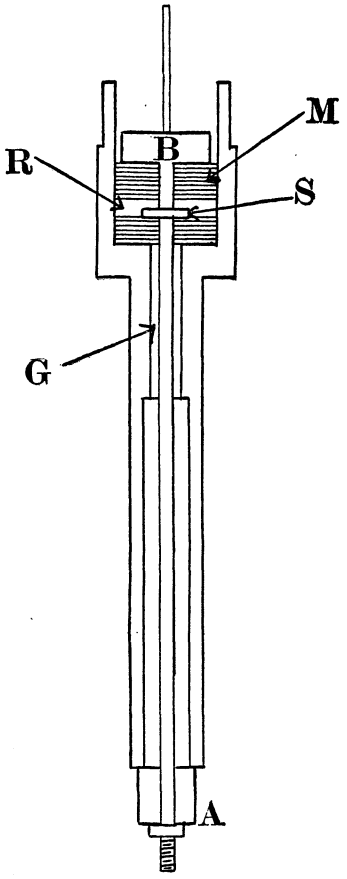

Figure 4. Final form of insulating plug. M, mica washers; R, soft rubber to prevent leak; S, steel washer to prevent leak of the rubber past the mica; G, insulating tube of glass; A, nut to keep the steel stem and the enlargement B from working loose.

reaching a steady value which is of the order of 100,000 ohms. The lowest resistance found in any of these plugs was 30,000 ohms. The resistance of these plugs was measured under pressure, all the conditions of the actual experiment as to position of the electrodes, etc., being reproduced, except for a dummy glass capillary to hold the mercury. When in use, the insulation resistance sometimes increased under pressure, the increase being sometimes as much as 100 per cent. This is still outside the limits of error, the error introduced in the above most unfavorable case being only one part in 6000 on the apparent resistance of the mercury. The performance was usually much better than this. Thus the insulation resistance of one plug which seemed to settle down after several applications of pressure at 150,000 ohms was found to be 220,000 after seven more applications of 7000 kgm.

In devising a form of vessel for holding the mercury, endeavor was made to keep the mercury as much as possible from contact with all sources of contamination by the use of platinum electrodes and a containing vessel entirely of glass. Other experimenters have allowed the mercury to come in contact with the steel of the containing vessel, using the vessel as one electrode, but this seems undesirable in view of the somewhat large effect of minute quantities of impurity. Many forms of glass containing vessel which readily suggest themselves are impractical because of the impossibility of using platinum electrodes sealed into the glass, the difference of compressibility between platinum and glass being sufficiently great to crack the glass around the electrodes. Two forms were finally adopted and used. The form first used was a U capillary (Figure 5), the electrodes dipping into the two cups at the upper end. In the form originally used this was made of thermometer tube of about 6 mm. outside diameter and 0.1 mm. bore. Several times, however, even when carefully annealed, the glass cracked at the bend, apparently because of the unequal strains set up by the hydrostatic pressure within

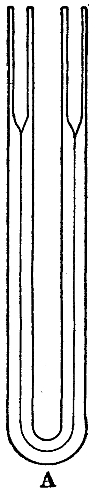

FIGURE 5. Original and final form of the receptacle for holding the mercury whose resistance is to be measured. If the glass is too thick, it invariably breaks under pressure at the bend A.

the glass, which must have been initially strained. This led to the adoption of a form in which there were no bends in the glass (Figure 6). The glass capillary (A) with the cup on the upper end for an electrode dips into the thin walled tube B containing mercury into which the other electrode dips. This form worked perfectly well, but was somewhat less convenient to handle than the U form. It was finally found that by making the stem of the U capillary very slender, about 1.5 mm., there was no tendency to crack at the bend, and this was the form with which the final determinations were made.

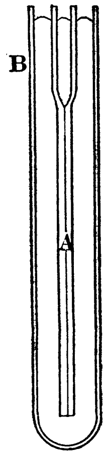

FIGURE 6. Alternative form of containing vessel for the mercury resistance. The resistance of the thin thread of mercury in the capillary A is measured. The containing vessel B must be of thin glass to insure freedom from breakage.

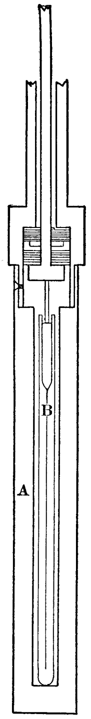

FIGURE 7. Manner of mounting the mercury resistance. The steel envelope A speedily conducts away the heat of compression.

The U capillary (B, Figure 7) is mounted in a split cylindrical piece of steel (A, Figure 7), which is attached to the lower end of the insulating plug. The capillary and plug may thus be connected together and inserted as one piece into the pressure chamber with the certainty that none of the connections will be disarranged in assembling. By making the split steel cylinder containing the U a snug fit, the glass is closely surrounded by metal on all sides, and the quantity of liquid transmitting the pressure is greatly diminished. This has the double advantage of decreasing the total change of volume of liquid necessary to reach a given pressure, and of decreasing the total heat of compression. The heat of compression generated in the small volume of liquid is so speedily conducted away by the metal that one has to work with inconvenient rapidity after increasing the pressure to find any trace of this effect. This seems to dispose of the only real advantage claimed by Lisell for the solid metallic resistance over the mercury gauge.

The electrodes are of platinum, one soldered to the outside shell of the plug, and the other to the inner stem, which is insulated from contact with the liquid by a layer of marine glue. The electrode leading from this stem is insulated with a soft fine rubber tube, except where it enters the cup of the capillary, where it is covered with a piece of glass tubing, joined continuously to the rubber above it with gutta percha. The electrode from the outer shell of the plug is also protected with glass where it enters the other glass cup. This precaution showed itself necessary, for otherwise if the platinum is not kept from contact with the walls of the cup the liquid above shows an appreciable tendency, with the successive lowerings and raisings of the surface by each application of pressure, to creep down the glass past the mercury.

There are several sources of error here that must be guarded against. Possible short-circuiting from one electrode to the other through the liquid has already been excluded by the measurements of the insulation resistance of the plug with a dummy capillary. In addition, the resistance of the electrodes between the mercury and the plug may change because of (1) lengthening of the free part of the electrode by depression of the mercury surface under pressure or distortions in the containing vessel, (2) pressure effects on the specific resistance of the platinum, (3) and change in resistance at the soldered connection between the electrodes and the plug. The first two sources of error may evidently be eliminated by using heavy enough electrodes. In this work electrodes 0.8 mm. in diameter were large enough. The third effect was found to be troublesome by Lisell, who avoided it by using long metal wires of resistance high in comparison with the resistance of the joint. No trace of this effect could be found, however, in this investigation. The absence of all three effects was tested by measuring the resistance when the terminals were short-circuited by dipping into a large tube of mercury, the resistance of the mercury now being negligible. In this case, the depression of the mercury due to compression is much greater than in the U capillary actually used. In the form tried, this depression may amount to 0.2 mm. Measurements were made up to 7000 kgm., and no change in resistance of the platinum terminal occurred of so much as $\frac{1}{1500}$ ohm, the smallest quantity that could be detected on the bridge. The possible error here, therefore, when the resistance to be measured is 10 ohms, is less than one part in 15000.

During the course of the experiments the steel cylinders containing the mercury resistance were placed in thermostats by which the temperature was usually kept constant within 0.01° during a day's work. Such constancy of temperature as this was not necessary, differences of temperature in the mercury of 0.06° being just perceptible on the bridge wire. Most of this work was carried out at temperatures of about 25°, which was high enough above room temperatures to insure the satisfactory performance of the thermostat. The temperature of the bath was read by a small Goetze thermometer graduated to tenths of a degree and calibrated at the temperature of the bath against a standard Tonnelot thermometer.

Before making the final calibration against the absolute gauge, many preliminary experiments carried out with varying success showed the necessity of observing rather carefully certain apparently insignificant matters of detail.

These preliminary tests were made by comparing together a number of pairs of mercury resistances, there being for this purpose two steel pressure cylinders to contain the resistances, two thermostats, and, as has already been mentioned, two bridge wires, either of which could be connected to the extension and balancing coils. The procedure in comparing two mercury resistances was: read resistance No. 1 on slide wire No. 1; throw in slide wire No. 2 and measure resistance No. 2; interchange the extension coils with the eight point switch and measure resistance No. 2 again; and finally throw in slide wire No. 1 and measure resistance No. 1 again. If these readings were made at equal intervals of time, as they usually were, the average of the two determinations of each resistance gives the value at the same instance of time. In this way the effects of slight changes of pressure due to dissipation of heat of compression and elastic after effects are eliminated. There was no leak. The pressure was roughly measured with the Bourdon gauge described above. These preliminary tests are competent to decide the question of the reproducibility of the mercury resistance gauge. The question of entire freedom from hysteresis, however, cannot be settled merely by a comparison of two gauges, for complete agreement would indicate only that hysteresis in the glass envelope was the same in either gauge. Entire freedom from hysteresis, within the limits of error, can be shown only by a comparison with the absolute gauge.

The results first obtained in the comparison of the two gauges were irregular beyond possibility of experimental error, discrepancies of 1 per cent being not uncommon. This was found to be due principally to three causes: minute impurities in the mercury, the effect of which will be discussed more in detail later; corrections due to air occluded in the mercury; and variations of elastic behavior of the glass envelope under pressure.

With the first few applications of pressure to the glass capillary directly after drawing, the zero value of the mercury resistance undergoes a permanent change, the magnitude of the change decreasing with successive applications of pressure until finally after four or five applications no further change is perceptible. This set is almost certainly due to a change of form of the glass vessel. This initial change has been observed as large as 3 mm. of bridge wire, that is, $\frac{1}{500}$ of the total resistance, and is always in the direction of decreased resistance, that is, toward an increase of cross section of the glass, contrary to what one might expect. If, however, this change of zero is caused by a relieving of the internal strains in the glass, it is in the direction one might expect, because the strains set up by drawing the capillary down from a larger size might decrease upon increasing the size toward its initial value. Not only is there zero change on the first application of pressure, but the elastic behavior over the entire pressure range, as shown by comparison with a well seasoned gauge, is irregular. This irregularity of behavior is shown independently of the resistance measurements by measurements of the compressibility of the glass, which will be given in another paper. The remedy for this defect is to season the glass by gradually applying and relieving the pressure several times. Sudden changes in pressure, such as have sometimes occurred when parts of the apparatus have exploded, are accompanied by large changes in the glass. If the glass has been subjected to considerable temperature changes after being seasoned in this way, it must be seasoned again before its indications are trustworthy.

Occlusion of air in the mercury is likely to cause considerable trouble if present in much quantity. Occluded air, as de Forest Palmer remarks, was doubtless responsible for the surprisingly large pressure coefficient of mercury resistance found by Lenz,[3] 0.0002. The complete removal of the air is difficult and was accomplished only once or twice. Boiling the mercury into the capillary several times is a fairly efficient method, but is open to the objection, as suggested above, that the glass must be seasoned again after each filling. Finally, after several attempts, the following somewhat extravagant method of procedure was found to work satisfactorily: One of the cups of the U capillary was nearly closed by a glass stopper, and the whole U tube was then placed in one of the two compartments of a glass vessel which was connected to a mercury pump and exhausted. Heat was then applied to the other compartment of the vessel which was full of mercury, and the mercury slowly distilled over until it covered the capillary, as high a vacuum as possible being maintained all the while by constant operation of the pump. This distillation acts as an additional purification of the mercury, that coming over being dry and presumably free from air. When the capillary was covered with mercury, air was admitted though the pump and mercury forced into the capillary through the open cup, any small possible bubble of air rising to the top of the other cup. In this way nearly all the air can be removed, the slight quantity remaining having probably clung to the inner walls of the capillary throughout the exhaustion. The quantity of air left was usually large enough to introduce an appreciable correction. This correction was determined by measuring the resistance of the mercury at low pressures compared with a calibrated Bourdon gauge of the Société Genevoise, and extrapolating back for the zero from 50 kgm. The tube must be refilled if the correction is large, because it will not remain constant, as obviously the effect of the occluded air on the resistance depends on its position as well as on its quantity. If the correction is small, however, it remains constant apparently indefinitely. In the tubes used, the correction ranged from 0.6 mm. to 0.1 mm. of the bridge wire, that is, a mean correction of about $\frac{1}{5000}$ of the total resistance. That the permanent change of the zero mentioned above was due to set in the glass and not to a curious behavior of the contained air, is proved by the fact that no set was found after filling in the manner above a tube once seasoned, but the correction for air assumed at once its final value.

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[3] Lenz, Wied. Beibl., **6**, 802 (1882).

In addition to showing the necessity of seasoning the glass and removing all air from the mercury, the preliminary comparisons showed that the mercury must be purified with some care. Later, a quantitive determination of the effect of two common impurities will be given. It was found that the mercury could be got sufficiently pure for present purposes by distilling commercial mercury, cleaning with acid, washing and drying, and finally distilling into the U capillary as described above.

When all these precautions are taken, the mercury gauge seems to be reproducible at pleasure. The results of a comparison of two such gauges is shown in Table I. The two mercury resistances compared were each contained in capillaries of the same kind of glass, Jena No. 3880 a. One capillary (R 9), however, was twice the linear dimensions of the other (R 10) because it seemed desirable to eliminate any possible effect of the size of the capillary on its elastic behavior. The smaller capillary, of course, was drawn down farther from the original piece, and so it is conceivable that the internal strains might be enough greater to result in different elastic behavior. In Table I the displacements of the slider of the bridge wire corresponding to the changes of R 9 and R 10, together with the ratio of the displacements, are tabulated against the approximate pressure, which was calculated from the comparison of R 10 later against an absolute gauge. The ratio is constant at 1.007, excepting two values, either of which could be brought to 1.007 by an error of only 0.1 mm. in the slider settings. The ratio of the resistance R 10 to R 9 multiplied into a constant expressing the different linear resistances of the bridge wires is also 1.007. Within the limits of error of the electrical measurements, therefore, or within $\frac{1}{10}$ per cent, the mercury resistance gauge may be assumed to be reproducible.

TABLE I.

COMPARISON OF TWO MERCURY GAUGES TO SHOW REPRODUCIBILITY.

Approximate Pressure kgm./cm.^{2}	Displacement of Slider in Cm.		
	R 10.	R 9.	Ratio.
1040	5.53	5.51	1.003
1930	9.81	9.74	1.007
2870	14.08	13.98	1.007
3750	17.47	17.35	1.007
4390	20.73	20.60	1.007
5650	24.61	24.45	1.007
6600	27.95	27.72	1.008
4250	19.59	19.45	1.007
1990	10.07	10.00	1.007

There is now left only one point in regard to the suitability of the mercury resistance as a secondary standard to be cleared up by the comparison of the mercury with an absolute gauge, namely complete freedom from hysteresis. The absolute gauge is that described in the first part of this paper. The steel parts of this gauge may of course show hysteresis, but if we assume that the liquid transmitting the pressure shows no hysteresis, which is almost certainly true, it is evident that any hysteresis effects in the steel parts will merely affect the correction for distortion of the gauge. The largest value of this is about $\frac{1}{10}$ per cent. Within the limits of error, therefore, the absolute gauge shows no hysteresis. Freedom of the mercury from hysteresis will be shown by agreement of the resistance measurements under increasing and decreasing pressure.

TABLE II.

Comparison of Mercury Gauge against Absolute Gauge at Increasing and Decreasing Pressures, to show Freedom from Hysteresis.

Pressure kgm./cm.^{2}	Slider Displacement Cm.	
	Increasing Pressure.	Decreasing Pressure.
917	4.89	4.89
1501	7.77	7.79
2018	10.17	10.19
2602	12.80	12.79
3196	15.35	15.37
3779	17.73	17.74
4233	19.49	19.51
4816	21.75	21.75
5348	23.70	23.65
5932	25.65	25.67
6452	27.45	27.43
6841	28.71	. . .

Comparisons of mercury resistance and absolute gauge were carried out with one mercury resistance (R 9) of soft Jena glass tubing No. 3880 a, and two absolute gauges, as has already been mentioned in the first part of this paper. The results of one of the comparisons under increasing and decreasing pressure, to determine freedom from hysteresis, are given in Table II. Here the displacements of the slider in cm. are tabulated against pressure, calculated from the corrected dimensions of the absolute gauge as described in the first part. The displacements under increasing or decreasing pressure agree within the limits of error of reading the position of the slider. Another comparison of R 9 against the same absolute gauge, as also a comparison against another absolute gauge, led to the same result. These comparisons were taken to afford sufficient proof of freedom from hysteresis of the mercury resistance in the soft Jena glass capillary within errors of $\frac{1}{10}$ per cent.

Having established the reproducibility and freedom from hysteresis of the mercury, we pass to the more important results to be obtained from the comparison with the absolute gauge, namely the final translation of the indications of the mercury gauge into kgm. per cm. The data used for this were those obtained from the two comparisons of R 9 against absolute gauge No. 1, and the one comparison against gauge No. 2. The results of these comparisons have already been given in Part I of this paper, where it appears that the two absolute gauges do not differ on the average so much as $\frac{1}{10}$ per cent from the mean. The average of these two comparisons is taken as the true value and is used in the following computations.

If the change of resistance is to be used as a practical standard of pressure, some empirical formula is desirable connecting the change of proportional resistance with the pressure. In the following, two formulas will be given, the first expressing the change of resistance in terms of the pressure, and the second, which will be more useful in practice, expressing pressure in terms of observed change of resistance. $\frac{\Delta R}{R_0}$ will be abbreviated by ρ, where ΔR is the observed change of the resistance in the soft envelope of Jena glass No. 3880 a, and R_0 the initial resistance measured in this envelope. Then ρ is some function of the pressure, approximately linear. A number of forms of this function were tried, it being desirable for convenience in computation to choose such a form that the number of empirically determined constants is small. It was at once obvious that the ordinary power series representation of the relationship was totally inadequate, at least five and probably more arbitrary constants being necessary to obtain $\frac{1}{10}$ per cent agreement over the entire range. Several other forms of power series tried, with fractional instead of integral exponents, were better, but not sufficiently approximate. Several exponential forms of the type $\rho = ap\,10^{P}$, where P is a power series in p, gave still better results. The form finally adopted was, $\rho = ap\,10^{bp^c}$, where

$$\log a = 5.5242 - 10,$$
$$\log (-b) = 6.2486 - 10,$$
$$c = 0.75.$$

This form does not lend itself to computation by least squares, and the best values for a, b, and c were found by trial. Table III shows the

TABLE III.

Comparison of Observed and Calculated Change of Resistance with Pressure.

Pressure kgm./cm.^{2}	$\frac{\Delta R}{R_0 p}$.		
	Calculated.	Observed.	Difference.
923	0.00003123	0.00003120	+3
1510	0.00003029	0.00003032	–3
2031	0.00002955	0.00002952	+3
2619	0.00002879	0.00002876	+3
3217	0.00002808	0.00002811	–3
3804	0.00002745	0.00002747	–2
4262	0.00002696	0.00002697	–1
4843	0.00002639	0.00002643	–4
5385	0.00002587	0.00002588	–1
5974	0.00002534	0.00002531	+3
6495	0.00002489	0.00002491	–2
6848	0.00002460	0.00002454	+6

$$\frac{\Delta R}{R_0} = -ap\ 10^{bp^{\frac{3}{4}}}$$
$$\log a = 5.5242 - 10$$
$$\log (-b) = 6.2486 - 10$$

observed values and the values calculated by the above formula, together with the discrepancies. The divergence is rarely more than $\frac{1}{10}$ per cent and seems irregular in sign. The fairly high discrepancy at 6800 is doubtless because this pressure was reached with only one of the absolute gauges, while all the other values are means of two determinations. The probable error of the formula itself, calculated by the formula for the error of the mean, is $\frac{1}{30}$ per cent.

TABLE IV.

COMPARISON OF OBSERVED PRESSURE WITH THAT CALCULATED FROM THE CHANGE OF RESISTANCE.

$\frac{\Delta R}{R_0}$.	Pressure kgm./cm.^{2}		Difference.	
ρ	Calc.	Obs.	Actual.	Nearest tenth %.
0.02880	925	923	+ 2	+2
0.04578	1512	1510	+ 2	+2
0.05995	2028	2031	− 3	−2
0.07532	2614	2619	− 5	−2
0.09044	3221	3217	+ 4	+1
0.10450	3810	3804	+ 6	+1
0.11490	4266	4264	+ 4	+1
9.12800	4856	4843	+13	+3
0.13940	5393	5385	+ 8	+2
0.15120	5969	5974	− 5	−1
0.16185	6507	6497	+10	+2
0.16810	6831	6848	−17	−3

$p = \rho a \, 10^{\beta \rho^{1.03}}$ $\quad a = \log 4.4871 \quad$ $\beta = \log 9.8836 - 10$

The above formula gives the measured change in the resistance of mercury in a specified glass envelope at 25° in terms of the pressure. In practice, it will be necessary to compute the pressure, given the measured change of resistance. The above formula cannot be easily solved for p, and another was set up giving p in terms of ρ. The form of this is exactly the same as for ρ in terms of p, and the procedure in determining the coefficients was the same. It was not found possible to get quite so good an approximation, however, partly because of the shape of the curve itself, which was such that a given percentage error in p produces less percentage error in ρ than the same percentage error in ρ produces in p. In practice, it will be found most convenient to find p graphically from a curve representing the relation between pressure and resistance. The form adopted was

$$p = \alpha \rho \, 10^{\beta \rho^{1.03}},$$

$$\alpha = \log^{-1} 4.4871,$$

$$\beta = \log^{-1} 9.8836 - 10.$$

Table IV shows the observed and computed values for p with the discrepancies. The probable error of a single reading is 0.12 per cent; that of the formula itself much less. This formula holds for mercury in soft Jena glass No. 3880 a at 25°.

At first sight it seems that the two empirical formulas may be combined by eliminating $\frac{p}{\rho}$ so as to give a single purely exponential relation between p and ρ which may be readily solved for either. This is not practical, however, because the exponential parts of the above expressions are only slightly affected as to percentage accuracy by relatively large percentage errors in the arguments, and therefore, inversely, small errors in the exponential part may produce large errors in the unknown (p or ρ) calculated from it. Errors of as much as 20 per cent were found to be introduced by the suggested elimination.

The above formulas are only empirical representations of the facts throughout a given pressure range, and their use by extrapolation over any considerably greater range is doubtful. No theoretical value is claimed for them, and it is evident that they cannot represent the actual form of the unknown function. Thus the formula for resistance in terms of pressure predicts a negative minimum of resistance of about -6 at 48,000 kgm. per sq. cm. Neither can extrapolation be carried entirely to the origin of pressure, for the formula demands that $\frac{d}{dp}\left(\frac{\rho}{p}\right)$ be infinite when $p = 0$, which is almost certainly not the case. The error here is slight, however, and confined to the immediate neighborhood of $p = 0$. $\frac{\rho}{p}$ at the origin remains finite, with nearly the same values as may be deduced from the formula for p in terms of ρ.

The above formula holds only when the mercury resistance is enclosed in a glass capillary of Jena glass No. 3880 a. If a different glass is used, it will be possible to use the formula by introducing a correction factor. This factor for one other glass, hard Jena combustion tubing No. 3883, was determined by comparing two mercury resistances. The comparison was made not so much with the idea that this hard glass would prove more convenient for practical use, but rather in the hope that these two different kinds of glass, one very infusible and the other very fusible, would show a comparatively large difference of compressibility. Table V shows the ratio of the observed changes of resistance in the hard and soft envelopes at different pressure. The mean of the ratios, weighted according to the magnitude of the effect measured, is 1.0266, while the ratio of the initial resistances is 1.0253. The difference between these two numbers is presumably due to the difference of compressibility of the envelopes, which turns out not to be as large as was expected from the character of the glass. The fact that the ratio of the change of resistances is greater than the ratio of the total resistances shows that

TABLE V.

EFFECT OF DIFFERENT GLASS ENVELOPES.

Pressure kgm./cm.^{2}	Ratio $\frac{\Delta R7}{\Delta R9}$.	Pressure kgm./cm.^{2}	Ratio $\frac{\Delta R7}{\Delta R9}$.
1170	1.025	5800	1.027
1950	1.025	6520	1.026
2960	1.027	4370	1.028
3830	1.028	2100	1.028
4700	1.025	...	...

Mean of ratios of change of resistance weighted according to pressure is 1.0266.
Ratio of initial resistances is 1.0253.
$R7$ is enclosed in hard Jena glass 3883.
$R9$ is enclosed in soft Jena glass 3880 a.

the hard glass is more compressible than the soft. That the difference is actually due to the difference of compressibility of the glass and is not an experimental error will receive experimental confirmation later by actual measurement of the compressibility of the glass. Resistances in hard as well as in soft glass envelopes may be used as standards, therefore, multiplying, however, the proportional changes of resistance in hard glass by 1.0013 to reduce to soft glass. But it will be noticed from Table V that the ratio of the changes of resistance in the hard and soft glass capillaries varies much more irregularly than the ratio for two capillaries of soft glass (Table I). That this is actually due to irregularities in the deformation of the hard glass will receive confirmation in the paper on compressibility. The hard glass is not so suitable, then, for the capillary as the soft Jena glass.

In practical applications of this gauge it will doubtless be inconvenient to work at the temperature above, 25°, and accordingly the temperature coefficient was determined over a range from 0° to 50°. The determination was made by comparing R 7, which was kept at the standard temperature 25°, with R 9, which was maintained during one set of readings at the given temperature over the entire pressure range. Comparisons were made at six different temperatures, 50.35°, 43.75°, 36.95°, 30.32°, 15.00°, 0.00°. At each temperature seven readings were made with increasing pressure and two with decreasing pressure to avoid all possibility of hysteresis, no evidence of which was found. In making this comparison it appeared necessary after each change of temperature to season the glass by preliminary subjection to the entire pressure range, the irregularities thus eliminated being greater the greater the temperature range. It was found that pressure may be calculated from temperature and the observed proportional change of resistance by the formula:

$$p = \alpha\rho\, 10^{\beta\rho^{1.03}} [1 - a_1 (t - 25°) - b_1 (t - 25°)^2],$$

where α and β have the values previously given, and

$$a_1 = \log^{-1} 7.1253 - 10,$$

$$b_1 = \log^{-1} 4.4487 - 10.$$

a_1 and b_1 were computed by least squares. It was evident on plotting the various points, that a_1 and b_1 are variable with the pressure, becoming less with increasing pressure, but the effect is very slight, and no systematic variation over the entire temperature range could be found. Attempts to introduce such a variation into the general formula would be beyond the accuracy of this work. Table VI shows the value of p computed by the formula for the two extremes of the temperature range. The observed pressures tabulated are the pressures computed from the change of R 7 after correction is applied reducing to soft glass. The difference column really contains, therefore, two sources of error. The differences are fairly small and irregular in sign. The irregularity is doubtless due to the incomplete seasoning of the glass by the previous single excursion through the pressure range, and the less regular behavior of the comparison resistance in the hard glass capillary.

TABLE VI.

Temperature Correction for Pressure in Terms of Resistance.

51.35°.			0°.		
Pressure kgm./cm.^{2}			Pressure kgm./cm.^{2}		
Obs.	Calc.	Diff.	Obs.	Calc.	Diff.
1074	1080	+6	1042	1037	− 5
1869	1864	−5	1879	1881	+ 2
2824	2825	+1	2845	2840	− 5
3641	3641	0	3637	3644	+ 7
4478	4478	0	4522	4524	+ 2
5470	5479	+9	5518	5522	+ 4
6527	6528	+1	6560	6573	+13
4249	4243	−6	4262	4256	− 6
1976	1969	−7	0015	2010	− 5

During the preliminary comparisons of different mercury resistances, the effect of a known slight quantity of impurity in the mercury was determined. The numerical values thus obtained are given here, as they may be of interest as showing the degree of purity which it is necessary to attain. It was found that metallic impurities have the greatest effect. Impurities that may be absorbed from the glycerine and water unavoidably in contact with the mercury appear to have no effect, as is shown by the constancy of behavior of the gauge over long intervals of time. To test the effect of small metallic impurities, two experiments were made on pure mercury contaminated with known quantities of foreign metal, in the one case 0.1 per cent of zinc, and in the other 0.1 per cent of lead. This is a very large quantity of impurity, much larger than can possibly occur in practice. On standing a short while in the air, the surface of the mercury becomes positively filthy with oxides. The effect of 0.1 per cent zinc is to decrease the resistance by about 1.4 per cent, but the pressure coefficient of resistance by about 5 per cent. Furthermore, the departure from the linear relation between total change of resistance and pressure is less than for pure mercury, being 3 per cent less at 6500 kgm. The results with the lead were not so satisfactory as those with the zinc. It was pretty certain, however, that the effect of the lead is less on the total resistance and greater on the pressure coefficient.

The formulas given above connect the change of resistance of mercury in a capillary of specified glass with the pressure, and are all that is required for use with a secondary standard of pressure. The observed change of resistance, however, is due to a combination of two unrelated effects; the change of dimensions of the glass, and the changed specific resistance of mercury. The results given above will not possess theoretical value, therefore, until the two effects are separated. In the following an experimental determination of these two effects is given.

We may distinguish two specific resistances of mercury, both of which are altered by pressure. The first may be called the specific volume resistance, and is the resistance of a body of mercury of invariable form, but of mass variable with the pressure. The second may be called the specific mass resistance of mercury, and is the specific volume resistance multiplied by the ratio of the masses within the given surface at the variable and standard pressure, i. e., the density. The specific mass resistance seeks to correct for the increased conductivity to be expected at any pressure because of the increased number of conducting particles in a given volume. In order to determine the specific volume resistance, the above results have to be corrected for the compressibility of the glass envelope; to determine the mass resistance, an additional correction must be applied for the compressibility of the mercury. These compressibilities are determined in another paper, to which reference must be made for the methods used. Only the results there found will be used here. It was found that for Jena glass No. 3880 a, $\kappa = 2.17 \times 10^{-6}$, and that the change of volume of mercury is connected with pressure by the relation

$$\frac{\Delta V}{V_0} = bp + cp^2,$$

$$b = \log^{-1} 4.5681 - 10,$$

$$-c = \log^{-1} 9.2977 - 20.$$

Now to find the changed specific volume resistance of mercury we have

$$\frac{\Delta R_s}{R_0} = \rho + \alpha p,$$

where ΔR_s is the observed decrease of resistance corrected for changed shape of glass, R_0 is the initial resistance measured in the same glass, α is the linear compressibility of the glass, and ρ has the meaning already given, namely the observed proportional decrease of resistance in the given capillary. But ρ has already been found in terms of p, and α has just been given, so that we have the empirical formula

$$\frac{1}{R_0}\frac{\Delta R_s}{p} = a\,[0.02168 + 10^{bp^{\frac{3}{4}}}],$$

where a and b have the values already given, namely,

$$a = \log 5.5242 - 10$$

$$b = -\log 6.2486 - 10$$

The slope of the curve, i. e., the instantaneous pressure coefficient at any point, is:

$$\frac{1}{R_0}\frac{dR_s}{dp} = -a\,[0.02168 + 10^{bp^{\frac{3}{4}}}\,\{1 + \tfrac{3}{4}\,bp^{\frac{3}{4}} \log_e 10\}],$$

where R_s is the variable resistance corrected for the glass. The instantaneous coefficient per unit resistance is at any point:

$$\frac{1}{R_s}\frac{dR_s}{dp} = -\frac{a\,[0.02168 + 10^{bp^{\frac{3}{4}}}\,\{1 + \tfrac{3}{4}\,bp^{\frac{3}{4}} \log_e 10\}]}{1 - ap\,[0.02168 + 10^{bp^{\frac{3}{4}}}]}.$$

These three quantities were computed by the above formula and are given in Table VII. They are also shown graphically in Figure 8, which indicates the general behavior without, of course, the accuracy of the formula. The general character of all these curves is the same, showing a continually decreasing effect of pressure on change of resistance as the pressure increases, this decrease itself also decreasing.

TABLE VII.

SPECIFIC VOLUME RESISTANCE OF MERCURY.

Pressure kgm./cm.^{2}	$\frac{1}{R_0}\frac{\Delta R_s}{p}$.	$\frac{1}{R_0}\frac{dR_s}{dp}$.	$\frac{1}{R_s}\frac{dR_s}{dp}$.
...	0.00003344	0.00003344	0.00003344
500	0.00003276	0.00003171	0.00003223
1000	0.00003182	0.00003011	0.00003111
1500	0.00003102	0.00002878	0.00003018
2000	0.00003031	0.00002760	0.00002938
2500	0.00002966	0.00002653	0.00002865
3000	0.00002906	0.00002552	0.00002796
3500	0.00002849	0.00002461	0.00002735
4000	0.00002795	0.00002374	0.00002674
4500	0.00002744	0.00002293	0.00002616
5000	0.00002696	0.00002216	0.00002561
5500	0.00002655	0.00002148	0 00002515
6000	0.00002603	0.00002073	0.00002457
6500	0.00002562	0.00002006	0.00002407

The curves do not run to high enough pressures to justify any speculation as to their ultimate behavior.

De Forest Palmer's are the only results with which these can be compared. He found $\frac{1}{R_0}\frac{\Delta R_s}{p}$ to have the constant value 3.224×10^{-5} between 0 and 2000 kgm.[4] There is, however, as already stated, a probable error of 1.5 per cent at 2000 kgm., and proportionally more

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[4] de Forest Palmer, Amer. Jour. Sci., **4,** 8 (1897).

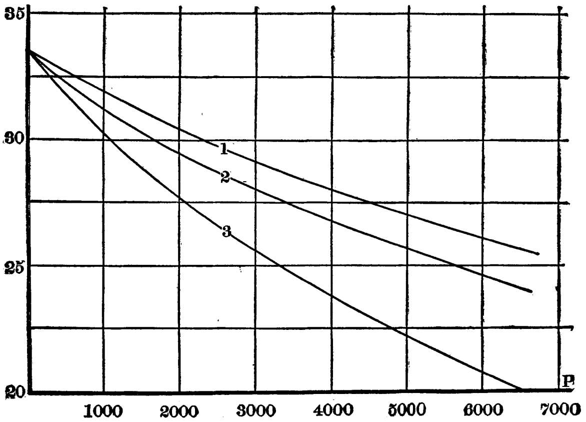

FIGURE 8. Various functions of the specific resistance of mercury plotted against pressure. 1 shows $\frac{1}{R_0}\frac{\Delta R_s}{p}$, 2, $\frac{1}{R_s}\frac{dR_s}{dp}$, and 3, $\frac{dR_s}{dp}$, where R_0 is the initial resistance and R_s is the variable resistance under pressure, corrected for the distortion of the glass containing vessel.

at lower pressures. According to the results above, $\frac{1}{R_0}\frac{\Delta R_s}{p}$ varies from 3.344 to 3.031 $\times 10^{-5}$ between 0 and 2000 kgm., giving a mean value of 3.187 $\times 10^{-5}$, which agrees within 1.1 per cent with de Forest

TABLE VIII.

SPECIFIC VOLUME RESISTANCE AND SPECIFIC MASS RESISTANCE OF MERCURY UNDER PRESSURE.

Pressure kgm./cm.^{2}	R_s.	$R_s \times D$.	Pressure kgm./cm.^{2}	R_s.	$R_s \times D$.
0	1.0000	1.0000	3500	0.9003	0.9114
500	0.9836	0.9854	4000	0.8882	0.9010
1000	0.9682	0.9716	4500	0.8765	0.8904
1500	0.9535	0.9588	5000	0.8652	0.8806
2000	0.9394	0.9462	5500	0.8540	0.8708
2500	0.9258	0.9342	6000	0.8438	0.8616
3000	0.9128	0.9228	6500	0.8335	0.8527

Palmer's value. In view of the magnitude of the variation found in the coefficient over the pressure range, the uncertain correction for the glass introduced by de Forest Palmer, and the magnitude of his probable error, this agreement is better than could be expected.

By combining the two empirical formulas for change of specific volume resistance and change of volume of the mercury, the value of resistance times density (*R·D*), i. e., the specific mass resistance, may be found. The departure of this from constancy may be described as the pure pressure effect on mercury resistance. In Table VIII the specific volume resistance and the specific volume resistance multiplied by the density are given for various pressures. They are also shown graphically in Figure 9. The curves are similar in all respects and show no indications of any remarkable behavior at higher pressures. The comparatively small part played by the change of density in the total change of resistance under pressure is of interest.

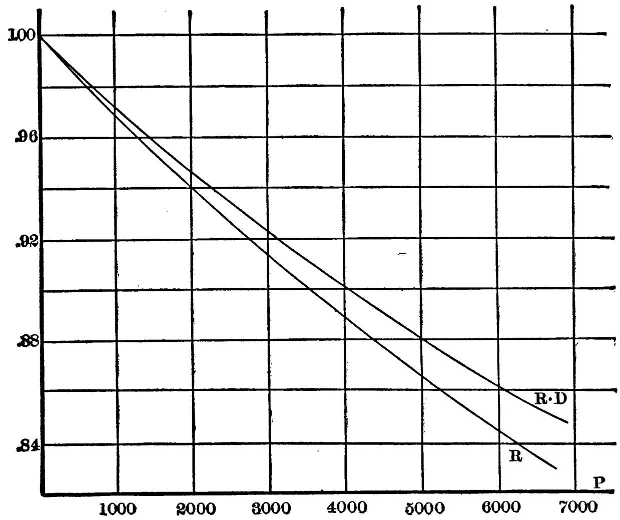

FIGURE 9. The changed resistance of mercury under pressure in terms of the resistance under zero pressure. The curve shows the measured resistance corrected for the distortion of the glass containing vessel. The curve R·D shows the former curve corrected for the changed density of mercury. It shows the pure pressure effect on resistance, that is, the resistance corrected for the increased conductivity due the increased concentration of the molecules. The smallness of the change of resistance due to this concentrating of the molecules is to be noticed.

Finally, the variation of specific resistance with temperature may be calculated from the formula given for the variation with temperature of p as determined by the measurement of ρ. Retaining only the term of the first degree in p, we have to the degree of experimental accuracy reached in these results:

$$\frac{\Delta R_s\,(p, t)}{R_s\,(0, t)} = \frac{\Delta R_s\,(p, t_0)}{R\,(0, t_0)} + a^2\, a_1\, \alpha\, p\, 10^{2bp^{\frac{3}{4}}}\,(t - t_0),$$

where a, a_1, α, and b have the values already assigned, and t_0 equals 25°. In the deduction of this formula the variation of the compressibility of the glass with the temperature was neglected. This variation is beyond the limits of error if the glass used has a temperature coefficient of the same order as that found by Amagat,[5] who found a change of 10 per cent for 100°. From this formula $R(p, t)$ was calculated for a number of pressures and for the temperatures 125°, 25°, and — 75°, assuming R (0, 25°) equal to unity, and taking for the temperature coefficient of specific conductivity the value 0.000888. These results are given in Table IX and plotted in Figure 10. This large temperature range was taken merely for convenience in showing

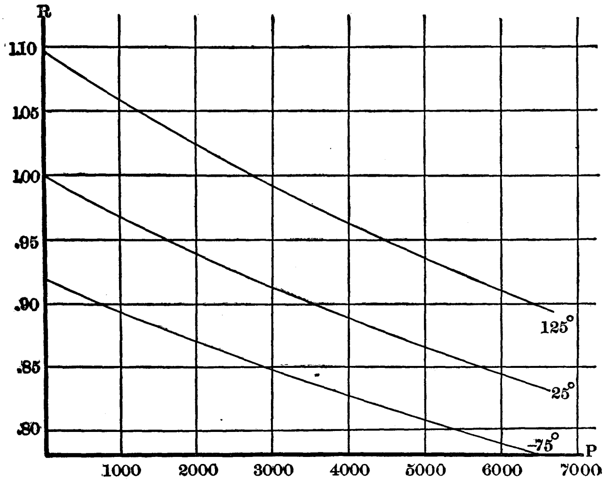

FIGURE 10. The resistance of mercury at various temperatures and pressures in terms of the resistance at zero pressure and 25°.

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[5] Amagat, C. R., **110**, 1248 (1890).

diagrammatically the general tendency of the results. The formula actually does not give results better than $\frac{1}{10}$ per cent beyond the range 0° to 50°. The temperature coefficient found above is nearly ten times de Forest Palmer's value, who, however, worked only at the extremes of a wider temperature range than that used here, namely, 9° to 100°.

TABLE IX.

Variation of Mercury Resistance with Pressure and Temperature.

Pressure kgm./cm.^{2}	R (p, −75°).	R (p, 25°).	R (p, 125°).
...	0.9186	1.0000	1.0970
500	0.9055	0.9831	1.0770
1000	0.8930	0.9682	1.0580
1500	0.8818	0.9535	1.0400
2000	0.8714	0.9394	1.0230
2500	0.8582	0.9258	1.0070
3000	0.8478	0.9128	0.9908
3500	0.8369	0.9003	0.9759
4000	0.8268	0.8882	0.9614
4500	0.8174	0.8765	0.9475
5000	0.8076	0.8652	0.9342
5500	0.7982	0.8540	0.9208
6000	0.7896	0.8438	0.9086
6500	0.7807	0.8335	0.8966

No theoretical discussion of the way in which these curves might be expected to behave has been attempted. Only a few points require remark. For instance, it is obvious from the table that temperature has a greater effect on the pressure coefficient of resistance than it does on the resistance itself. The temperature coefficient of the former is 0.00137, and of the latter 0.000888. In other respects the curves behave as one would expect, i. e., at higher pressures the proportionate effect of temperature is reduced. This is shown by the temperature effect both on resistance and on pressures coefficient of resistance. Thus the temperature coefficient of the pressure coefficient has become reduced at 6500 kgm. to 0.7 of its initial value, while the temperature coefficient of resistance is reduced from 0.0009 to 0.0007. This latter effect shows itself in a tendency of the curves for different temperatures to draw together with increasing pressure toward some value of resistance greater than zero. That is, for a large enough value of pressure, the resistance acts as if it might have a definite value independent of temperature.

CONCLUSION.

In this paper it has been found that the mercury resistance gauge is a reliable secondary standard of pressure if proper precautions are used. The mercury must be pure and free from air. The irregular behavior under pressure of the containing glass capillary is the principal source of error. An easily fusible glass in which the strains left after drawing are presumably small, is better than an infusible glass. The glass must be seasoned by several applications of pressure over the entire range before it becomes regular in behavior. If after this it is exposed to considerable changes of temperature or to sudden changes of pressure, it must be reseasoned. The maximum error that can be introduced by irregularities in the glass is about 2.5 per cent. The dependence of pressure on the measured proportional change of resistance (p) and temperature is given by the equation

$$p = \alpha \rho \, 10^{\beta \rho^{1.03}} [1 - a_1 (t - 25^\circ) - b_1 (t - 25^\circ)^2],$$

where

$$\alpha = \log^{-1} 4.4871;$$

$$\beta = \log^{-1} 9.8836 - 10;$$

$$a_1 = \log^{-1} 7.1253 - 10;$$

$$b_1 = \log^{-1} 4.4487 - 10.$$

This formula, which applies to mercury in a capillary of Jena glass No. 3880 a, gives the pressure correctly to $\frac{1}{10}$ per cent between 500 and 6800 kgm. and 0° and 50° C.

Empirical expressions have also been deduced connecting the specific volume resistance and the specific mass resistance of mercury with the pressure.